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NEW GRAVITATIONAL FORCES FROM QUANTUM THEORY

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ABSTRACT

When a classical theory is quantized, new physical effects result. The prototypical example is the Lamb Shift of quantum electrodynamics. Even though this phenomenon could be parametrized by the "Uehling Potential", it was always realized that is was a quantum aspect of electromagnetism, not a "new force" of nature. So, too, with theories of quantum gravity. Generically they predict that there will be spin-1 (graviphoton) and spin-0 (graviscalar) partners of the spin-2 graviton. At some level, these partners will generate new effects. Among them are i) non-Newtonian gravitational forces and ii) substance dependence (violation of the Principle of Equivalence). We discuss these ideas in the context of recent experiments. (Experiments usually test only one of the above two effects, which could be distinct.) We contrast these ideas with the alternative point of view, that there actually may be a "fifth force" of nature.

The work which I am discussing had its genesis in the proposal a number of years ago[1], that one should measure the gravitational acceleration of antiprotons. Of course, this proposal developed from our particle physics background, and from the question of how one can approach gravity from there. Since then our ideas have progressed much further[2-5]. To put our ideas in an historical perspective, let me review how particle physics has come to the outlook that it has.

By the beginning of the 1800's, physicists (or "natural philosophers") had come to believe that there were three forces in nature, electricity, magnetism, and gravity. From the work of such scientific giants as Faraday, Oersted, and Maxwell, physicists came to realize over the next half-century or so that electricity and magnetism are simply two aspects of the same force. By the beginning of this century, experiments on radioactivity and the atom manifested aspects of what would later become known as the strong and the weak forces.

At this time, Einstein put relativity into gravity, yielding the classical (i.e., non-quantum) theory that is the basis of our understanding today -- general relativity. Now if one applies general relativity to the precession of Mercury's perihelion, one finds a force term that varies as $1/r^3$. However, one does not say that this is a new force of nature. One says that this is a new aspect of gravity which manifested itself when relativity was put into gravity.

In the same way, when quantum mechanics was applied to electromagnetism in the 1920's, there were new effects which were seen. These new effects were not due to a new force of nature: Maxwell's equations were not changed classically. Rather, these new effects came about because quantum mechanics had been put into Maxwell's equations.

The most illuminating example of this is the phenomenon we now call the Lamb shift: the energy difference between the $2P_{1/2}$ and $2S_{1/2}$ levels in hydrogen. In the 1930's this energy shift was parametrized by the "Uehling potential." However, nobody claimed this potential manifested a new force. Rather, it was understood to be a new aspect of electromagnetism from quantum mechanics.

Today the main thrust of modern particle theory is to try to unify all the forces of nature in a relativistic, quantum field theory. This is in the spirit of the unification and quantizing of electricity and magnetism. The work of Weinberg, Salam, and Glashow in the 1960's and 1970's resulted in the unification of electromagnetism with the weak nuclear force, into what we call the electroweak theory[6].

Independently of the above triumph, a model of the strong force was advanced. It is called QCD, for quantum-chromo-dynamics[7]. QCD has not yet been unified with the electroweak theory. The hope was, up until recently, that QCD and the electroweak theory could be unified by the group SU(5). but a strong prediction of this theory is that the proton will decay with a lifetime $< 10^{32}$ years[8]. Unfortunately, although many experiments were mounted to detect this decay, none did, so the strong and electroweak theories remain to be unified.

However, this in no way inhibits particle physicists from attempting even more grandiose schemes. Even though the electroweak and strong theories are not unified, theorists are already trying to unify these theories with gravity. Such theories[9] are generally called "quantum gravity theories." One of the aspects of these theories is that, as with electromagnetism, new gravitational effects arise because quantum mechanics is brought into the picture

Before going on, however, I should emphasize that none of these new theories has as yet produced a viable set of physical predictions, such as a verifiable particle spectrum (even though there is a tendency to declare, "Wait until the next accelerator!"). Therefore, these theories are theories of theories for now, but they all have tantalizing phenomenological features. These features are generic, even though they come from theories with many physical motivations: supersymmetry, dimensional-reduction, strings.

Most importantly, in these theories, the spin-2 graviton has spin-1 (graviphoton) and spin-0 (graviscalar) partners. These partners are expected to have a finite rest mass (and so violate the inverse-square law), and may couple to the fundamental fermions in the theory (and so violate the weak equivalence principle). Indeed, in general there are many partners of each spin, which will have different masses (ranges). Keeping only one new partner of each spin for simplicity, one has, in the linear approximation, that the interaction energy from gravity is

$$I = -(G_\infty M_1 M_2/\gamma_1\gamma_2 r)\ [2(u_1\cdot u_2)^2 - 1 \mp a(u_1\cdot u_2)\exp(-r/v) + b\ \exp(-r/s)]\ . \qquad (1)$$

The first term is Newtonian gravity. The second term is from the graviphoton. The two signs correspond to the fact that the sign of a vector interaction depends upon the charges of the particles interacting. As in electromagnetism, likes repel and opposites attract. Here the charges are "matter" and "antimatter", specifically represented by, for example, a linear combination of baryon and lepton number. The graviscalar term, like the tensor term, is always attractive. Note that the above terms have different velocity-dependences. Using a model of millisecond pulsars, we have used this fact to set a limit on the size of the two new coupling constants[3]. Under the assumptions that the couplings are approximately equal and that the ranges are at least on the order of a pulsar radius, we find that the couplings must be approximately $< 70\ G_\infty$.

In the static approximation, the potential takes the form

$$V = -(GMm/r)\ [\ 1 \mp a\ \exp(-r/v) + b\ \exp(-r/s)\ ]\ . \qquad (2)$$

If, to a good approximation $a = b$ and $v = s$, then a surprising result could ensue. One could have that for matter-matter interactions the two new terms could approximately cancel, yielding a small new effect, and yet for matter-antimater interactions the two new terms could add, yielding a realtively large new efffect.

A question which arises at this point is: "does a different gravitational acceleration for antimatter violate CPT?". The answer is, "No!" There is confusion because we are dealing with two concepts of mass, and also both with classical gravity and quantum mechanics.

The first concept of mass is the gravitational mass, m_G. This mass is a charge, the charge in Newton's Law of gravitational force:

$$F = -Gm_G m_{G'}/r^2 \quad . \tag{3}$$

The second concept is the intertial mass, m_I. This mass is a kinematic quantity, the object found in Newton's Law of Force,

$$F = m_I a \quad . \tag{4}$$

The Principle of Equivalence tells us that an object's *gravitational mass for tensor gravity* is equal to its *inertial mass*:

$$m_I = m_G \quad . \tag{5}$$

CPT tells us that the inertial mass of a particle is equal to the inertial mass of an antiparticle:

$$m_I = \bar{m}_I \quad . \tag{6}$$

However, even though Eqs. (5) and (6) are true, it does not mean that the gravitational attraction of an antiparticle must be the same as that of a particle. Actually, CPT only tells us that an apple dropped to the earth will have exactly the same acceleration as an antiapple dropped to an antiearth. CPT doesn't tell you what happens if an antiapple is dropped to the earth.

There are two main schools of thought on the arguments I have just given. The school to which we belong has just been explained. It holds that if there are new forces of approximately gravitational strength, then obviously one is seeing new parts of gravity.

The loyal opposition feels that there actually may be an entirely new force in nature, a "fifth force," even though it is approximately of gravitational strength. They argue that, just as Einstein was unsuccessful in unifying gravity with electromagnetism because there were other (weak and strong) forces that had to be dealt with, so too now we can not have a unified theory without an entirely new force.

Even though we oppose the "fifth force" school on intuitive physical grounds, this is a question which ultimately will be settled by experiments and theoretical understanding of them. So what do experiments say? The results are mixed and fascinating, to say the least.

These experiments will be reviewed elsewhere at this conference, but I wish to make a few main observations. As to tests of the Principle of Equivalence, with the notable exception of Thieberger's experiment at the Palisades site[10], all recently reported results have found no effect[11-13], or a very small one[14]. On the other hand, all recent tests of the inverse-square law for length scales of the order of hundreds of meters to perhaps hundreds of kilometers have found anomalies[15-18]. This includes the recently announced result of the Greenland ice-sheet experiment, which my friend and colleague, Mark Ander, is describing at this meeting[18].

Could it possibly be that there is no violation of the Principle of Equivalence but yet a violation of the inverse-square law? This would be contrary to everyone's (including our) expectations. The possibilities here are fascinating.

I want to conclude with a status report on what started us all on this, the gravitational acceleration of antimatter. Los Alamos is involved in an international collaboration to perform an approved experiment at LEAR, the low-energy antiproton ring at CERN. This is a "Galileo" experiment, which measures the time-of-flight of antiprotons up a drift tube. The experiment is undermanned and underfunded, of course, but it is proceeding. The final magnet for the catching trap is in the lab; the design of the drift tube and magnet for it are approaching completion; tests will be done this fall at LEAR to study the spectrum of antiprotons coming out through a foil from LEAR, and studies of cooling techniques for the antiprotons in the catching trap are underway. Hopefully, the experiment will be on the floor in 1991.

I should also mention that a complementary experiment[19] to measure the gravitational acceleration of positrons is being explored by Bill Fairbank[20]. Bill and Fred Witteborn (a member of our collaboration) pioneered the use of drift tubes for gravity measurements.

As you can see, we find this a very exciting time for gravity, and we hope that you all share in our enthusiasm.

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